THE DESIGN AND CONSTRUCTION OF AN APPARATUS FOR DETECTION OF PROTON-ALPHA NUCLEAR REACTIONS

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THE DESIGN AND CONSTRUCTION OF AN APPARATUS FOR DETECTION OF PROTON-ALPHA NUCLEAR REACTIONS

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By

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I. Introduction.

A. Proton-Alpha Reactions.

The basic nuclear equation for the proton-alpha reaction is as follows:

$$ {}_{Z}X^{A} + p \longrightarrow {}_{Z-1}Y^{A-3} + \alpha + Q \quad . $$

This may be made into an equality if all terms are expressed in either energy or mass units - energy and mass being interconvertible by Einstein's equation:

$$ E = mc^2 $$

Q represents the amount of energy (or equivalent mass) required to balance the equation, and shows up as the difference between the kinetic energy of the resultant particles and the kinetic energy of the initial particles. If Q is positive the incident proton need not provide any kinetic energy to the reaction to make it energetically possible; but if Q is negative the reaction can proceed only if the proton has sufficient kinetic energy to overcome the unbalance (plus an amount - usually small - to give motion to the center of mass of the system).

This particular reaction is for a great many isotopes exothermic (that is, Q is positive), primarily because of the fact that the alpha particle with its large mass defect is quite economical in the amount of mass it carries off from the resultant nucleus. The reaction is particularly likely to be exothermic for odd Z, since the product

nucleus turns out to have even Z and opposite A - which are known in general to have a greater mass defect than the parent nucleus. For a similar reason a target nucleus of even Z is least likely to give an exothermic reaction.

Whereas in theory any exothermic reaction can be produced with incident particles of low energy, in practice the yield may be so low as to make the reaction undetectable. This is especially true in the case of the proton-alpha reaction, because of the Coulomb potential barrier surrounding thenucleus. Such a barrier tends to keep the incident protons out and to retain alpha particles trying to escape. The height of this barrier is not accurately known but has been estimated to be given approximately by the equation(23):

$$U = 0.72 \times Z^{2/3} \quad (\text{Mev}) \quad .$$

This means that for reactions which may be induced by protons of energies usually available from a Van de Graaff generator, the height of the potential barrier except for very light elements is always much greater than the energy of the incident particle. Classical mechanics forbids the protons from ever existing in a region where the potential energy is greater than the total energy level, which fact would seem to prevent the proton from ever entering the nucleus. Modern concepts of quantum mechanics, however, specify that the possibility does exist for the proton to be in this traditionally forbidden region close to the nucleus, even though the potential barrier is higher than the energy of the proton. Analyses

of barrier penetration have been made which indicate that the possibility of particle penetration, though small as a rule, does increase as the particle energy becomes greater or the barrier height is lowered.

Another factor which must be considered is the "sticking probability" , or the chance that the proton, once in the range of nuclear forces, will merge with the other nucleons to become an integral part of the nucleus. Finally there must be considered the probability that the nucleus will cast out the product particle (in our case the alpha particle) before the nucleus stabilizes itself by a different process. Said particle must be formed more or less as an entity in the nucleus and penetrate the barrier in the same quantum-mechanical sense as the entering particle does.

From the above considerations one arrives at the overall probability of the occurrence of the reaction in question. This may be expressed by the word "cross-section", which is defined as the probability that one incident particle, impinging on the target material having one nucleus per square centimeter of area normal to the direction of impingement, will bring about the reaction. Under usual conditions we see that the reaction cross-section for the proton-alpha reaction will in general increase with proton energy.

At so-called "resonance" points, sharp peaks in the cross-section versus energy curve occur, which are superimposed upon the general rising cross-section. These resonances are analogous to resonances in classical oscillator systems; and one may occur where the in-

coming particle has just the right energy to excite an energy level of the resulting compound nucleus. In determination of these resonances experimentally, the conditions must be precisely and carefully regulated. The prediction of the places where resonances occur is difficult from pure theory, since no theoretical means has been found to specify exactly where energy levels of the compound nuclei exist. Experimental data is also far from complete. In a general sort of way it may be said, nonetheless, that as Z of a nucleus increases, the energy levels come in closer to the ground state energy level, become more closely spaced, and also become broader. For nuclei of high Z the levels are so broad and close together as to fade into one another and lose their discrete quality, thus preventing observations of any resonances. For a value of Z in an intermediate region perhaps one may detect resonances for our reaction; and as stated previously there seem to be many exceptions to the general rules outlined above which may permit such an observation. Such an observation is facilitated by good energy resolution in the protons as might be expected from a well-regulated Van de Graaff generator.

Another aspect of the proton-alpha reaction in moderately heavy elements is the possibility that the alpha particle will not carry off all the kinetic energy available to it, but leave the resultant nucleus in an excited state. This requires of course that the nucleus has an excited state low enough that the alpha particle may still have sufficient energy to penetrate the potential barrier with reasonable probability. Usually in this case, the alpha particle emission is followed almost immediately (within 10^{-14} to 10^{-12} seconds) by gamma

emission. This is sufficiently close to be considered a coincident effect and may be measured as such since coincidence counters record events which are separated by as long as 10^{-6} seconds. For those residual nuclei which do not have too low a value of Z the number of energy levels which may be left excited following alpha emission from the compound nucleus may be quite a few, which gives a high probability of gamma emission accompanying the alpha emission. (Parity considerations may enter into the establishment of allowed gamma transitions.)

Directional preferences may be displayed by the emitted particle (and photon, if occurring). Since the entering proton may carry with it a certain angular momentum, the vector of which is oriented at random in a plane perpendicular to the direction of motion of the proton beam, the compound nucleus as it decays to the ground state of the resultant nucleus may get rid of this angular momentum by emitting radiation in a direction which is preferentially oriented to the said plane. This indicates that the detection of gamma rays, either alone or in coincidence with the alpha particles, may have a variation with the angle of emission.

B. Possibility of Proton-Alpha Reactions in Elements with Z from 26 to 29.

The metallic elements - iron, cobalt, nickel, and copper - are particularly worthy of investigation for the proton-alpha reaction. They are somewhat above the "light" element range, but not too far above to make the reaction impossible of detection using a Van de Graaff of 2 Mev maximum energy. Also in this region of masses emission. This is sufficiently close to be considered a coincidence effect and may be measured as such since coincidence circuits record events which are separated by as long as 10^{-6} seconds. For those residual nuclei which do not have the low I value of 0 the number of energy levels which may be left excited following alpha emission from the compound nucleus may be quite large, which gives a high probability of gamma emission accompanying the alpha emission. (Parity considerations may enter into the establishment of allowed gamma transitions.)

Directional preferences may be introduced by the emitting particle (and photon, if coincident). Since the incoming proton may carry with it a certain angular momentum, the vector of which is oriented at random in a plane perpendicular to the direction of motion of the proton beam, the compound nucleus as it exists in its ground state of the residual nucleus may get rid of this angular momentum by emitting radiation in a direction which is preferentially oriented in the same plane. This indicates that the detection of gamma rays, either alone or in coincidence with the alpha particles, may have a variation with the angle of emission.

4. Possibility of Proton-Alpha Reactions in Elements with A from 50 to 60.

The metallic elements — iron, cobalt, nickel, and copper — are particularly suited to investigation for the proton-alpha reaction. They are [illegible] than the "light" element group, but not too far [illegible] [illegible] the expected [illegible] of detection [illegible] [illegible] the [illegible] of a [illegible] [illegible] energy. [illegible] in this region of atomic resonances may possibly be detected and the expected energy levels of the residual nucleus are low enough that gamma ray emission may be associated with the alpha particle emission.

The stable isotopes of the above elements are as follows: (25)

Element	Z	A	% Abundance
Fe	26	54	5.81
		56	91.66
		57	2.20
		58	0.33
Co	27	59	100.
Ni	28	58	67.76
		60	26.16
		61	1.21
		62	3.66
		64	1.16
Cu	29	63	69.09
		65	30.91

Cobalt and copper isotopes have odd Z, and therefore in general are more likely to enter into exothermic reactions.

It is possible where the product nucleus is a stable isotope, whose mass is known fairly accurately, to compute the value of Q on the basis of equality of mass-energy. This gives a formula as follows:

$$Q = (M_{Target} - M_{Product} - 2.99578) \times 931;$$

where $2.99578 = M_{\alpha} - M_p$.

Using this formula where possible the following values of Q are obtained: (1),(2),(9),(10),(15),(16),(21),(22)

Target	Z	A	M_T	M_P	Q (Mev)
Co	27	59	58.95068 ±.00035	55.95285 ±.00016	1.91 ± .36
Ni	28	62	61.94822 ±.00045	58.95068 ±.00035	1.64 ± .53
Cu	29	63	62.95032 ±.00041	59.94840 ±.00030	5.71 ± .47
	29	65	64.94884 ±.00032	61.94822 ±.00045	4.50 ± .51

The potential barrier height for those elements is on the order of 6 to 7 Mev, which will not permit a large reaction cross-section but will, it is hoped, give a detectable number of reactions.

C. Detection of Proton-Alpha Reactions.

The production and detection of the proton-alpha reaction are complicated by the fact that both of these particles are heavily ionizing in matter. This means that if one or the other of the particles passes through matter before the final detection, it loses its energy rather easily; and for the same reason discrimination between the two types of particles is difficult as a rule. For reactions involving a high positive value of Q, these difficulties are minimized since the alpha particle becomes relatively penetrating and gives a large ionization trace in any detection apparatus.

The methods of producing and detecting the reaction are all standard and orthodox. Protons are usually produced by accelerators such as the linear accelerator or the Van de Graaff generator. These are ac-

celerated in a vacuum and are incident upon the target, usually a foil which may be coated as required. Detection of the emitted alpha particles is accomplished by several means - scintillation screens (originally counted by eye, but now by photomultiplier tubes and associated electronic circuits), identification of tracks in a photographic emulsion, or by the usual type of alpha gas-filled counters. Alpha ray energies are usually determined by having the particles pass through a magnetic field, such as a magnetic spectrograph, which can sort out and provide a means of measuring the e/m ratio of the charged particles passing through.

D. Method of Detection to be Used in This Design.

The object of the design undertaken for this research has been to provide an instrument which will not have the complexities in construction and use which most of the usual ones have; but will still be fairly sensitive in detection and give at least roughly quantitative data on proton-alpha reactions. The basic principle of our design requires that the reaction occur within the counting apparatus, so that the alpha particles have little matter to traverse before reaching the detection zone. The detector proper is to be a proportional counter, with attached electronic discriminator, which will permit separation of alpha particle pulses from proton pulses in the process of counting. The particle beam is to be collimated to the extent necessary to cause the particles to traverse the sensitive region roughly parallel to the longitudinal axis. This permits maximum ionization, and consistently-sized pulses

for particles of similar type and energy.

Protons are introduced at a very acute angle into the apparatus, so that the scattering angle will be large and provide a minimum of the scattered protons. The window for entry of the protons is to be of a thin foil. (Nickel foil of .00005" is available, and is stated to be able to hold about an atmosphere of pressure differential over a hole of area 1 square centimeter.) The energy loss of the proton beam through the foil is accepted, but is determinable and under most circumstances is only a small fraction of the beam energy.

II. Description of the Apparatus

A. Mechanical Parts.

The apparatus designed and built in the prosecution of this research is shown in Figures 1 and 2. The detection device proper consists of four parts: (1) the connecting piece which is attached between glass insulators at the end of the proton tube in the magnetic analyzing section of the Van de Graaff generator; (2) the "Faraday cage" which receives the protons and collimates them in a narrow beam to pass through the nickel foil; (3) the reaction chamber, which holds the target in such a position that it may receive all the protons, and may emit some of its alpha particles into the counting chamber; and (4) the counting chamber itself, which is similar to most gas-filled radiation detecting devices - collecting ionization pulses from the particles passing through its sensitive volume via a small port in the reaction chamber.

The connecting piece has on it a flexible and gas-tight sylphon tube which aids in lining up the apparatus with the proton beam from the generator. It is otherwise simply a straight tube. The "Faraday cage" is so called because Faraday originally noted the fact that such a hollow body has no field on the inside, and it acts as a bucket catching the protons. It is placed at a positive potential with respect to the connecting piece in order to minimize loss of electrons back-scattered from the foil as protons hit it.

The reaction chamber is electrically, though not mechanically, integral with the Faraday cage portion. The latter may be simply

inserted or withdrawn from the side tube which holds it, permitting easy assembly. The reaction chamber is designed so that the protons may be sent through a foil target and eventually caught behind the target in such a way that scattering of the bombarding particles into the counting chamber is highly improbable. In this way only protons scattered at the given angle (150°) by the target itself can get to the sensitive volume.

The port through which the particles pass is small so as to reduce the interfering proton scatter, and also to collimate the alpha particles to the extent necessary to prevent their hitting the walls of the sensitive volume. This insures that all alpha particles of the same energy leaving the target will give approximately the same ionization in the counter.

The reaction section (including the Faraday cage) is insulated from the remainder of the apparatus. This permits it to be maintained at a voltage level above its adjacent parts. As indicated above, this helps retain any electrons emitted by charged particles striking any part of the apparatus. This is necessary in order to conserve the charge on this part, for the reaction chamber is attached electrically to a current integrator of some sensitivity which counts the charge accumulated in the proton bombardment. This gives a measurement of the flux of protons.

The counter is operated in the proportional region. It has valved side ports which are required for gas filling and for the mercury manometer hose connection. Any pressure of gas desirable (within limits

imposed by fragility of the proton window, voltage on the central wire, etc.) may be admitted. Multiple connections are provided so that gas mixtures may be used.

A vacouum hose is provided between the counter chamber and the connecting piece which permits placing the vacuum simultaneously on all parts of the apparatus when the valves are all open. The vacuum may be provided by a mechanical pump or by the pumping apparatus of the Van de Graaff generator itself when in actual operation. After the vacuum is obtained, then the valve in the connecting hose is closed, and the counter may be filled as required with the proper gases.

B. Electronic Portion.

The electronic parts of the apparatus,though more or less standard for proportional type counters, were selected especially for the project at hand, and may therefore deserve a brief description.

The central wire of the counter (5-mil nickel wire) receives its high positive voltage (around 500 to 1000 volts) from a special power source obtained from Nuclear Instrument and Chemical Corporation. It is Model 1090 5000-v. Regulated Power Supply. It can give positive or negative voltage from zero to maximum value, and is regulated to within 0.02% of output voltage.

The pulse of current associated with electron collection on the central wire and positive ion movement goes to a cathode follower, especially designed to have a time constant on the order of a microsecond, permitting quite rapid recovery of the counter. The follower has no amplification but provides enough power to prevent diminution

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in the transmission of the impulse to the remainder of the circuit.

The signal is picked up by a linear amplifier and discriminator, the Atomic Instrument Company's Linear Amplifier, Model 204-B. This amplifier is able to recover very quickly from input signals. It may be set for rise times of 0.2, 0.8, or 5.0 microseconds, with signal decay times on the order of five times the rise times. Variable voltage ~~amplification~~ attenuation is provided - from 1 to 64. A discrimination circuit may be cut in as desired. The discrimination permits cutting out of all signals below a certain set level. The discriminator section sends out 1 microsecond, 10-volt pulses regardless of the strength or duration of the incoming pulse.

The output of the discriminator is sent to a scaler circuit of standard type. The one used here is the Autoscaler sold by Tracerlab, Inc. It has a timer mechanism which allows, if desired, automatic cut-off after a pre-set number of counts from 2 to 4096 (by powers of 2).

The whole assembly is mounted in a movable steel rack, with wire mesh panel sides for shielding purposes, and a similar type removable cover. This is to minimize stray signal pick-up from all other electric apparatus in the vicinity.

C. Window Foil.

The window is a nickel foil, 0.00005" thick, plated on a copper backing about 20 times as thick. The foil was manufactured so as to be free of pin-holes, and to be of a very even thickness. Furthermore, since it can withstand an atmosphere of pressure across an

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area of 1 square centimeter, according to the manufacturer, it is strong enough for our use, as it has to cover a hole of somewhat less area and is not expected to withstand more than 400 mmHg of pressure. In mounting the foil window, the following procedure was used: glyptol was placed on the end of the Faraday cage tube, allowed to dry slightly to a maximum stickiness; the foil was then laid on carefully (nickel side on the glyptol) and gently but firmly pressed on. After a short drying period, the foil was trimmed around the edges and further glyptol applied at this circumference. After complete drying of all the glyptol the tube (also protected by a painting of glyptol) was hung, foil side down, in a mixture of ½N. trichloroacetic acid and concentrated ammonium hydroxide (48%) in approximate ratio of two to one. This dissolves the copper in the form of a soluble copper complex ion, and leaves the nickel foil intact.

D. Insulators.

The spacing insulators between the sections are made of lucite. These are rendered gas-tight in the assembly by O-rings, placed in grooves machined correspondingly in the lucite and adjacent metal sections. The lucite insulators are drilled for screws to pass through, and they are connected at the periphery alternately to the metal sections on either side. When the nuts are tightened on the screws, bending stresses would be put on the insulators; and for this reason brass annular flat rings were inserted in spaces cut out in the lucite to take the bending stresses. (Lucite alone, it was found, is rather flexible up to a point, and then cracks rather easily under tensile

stress.)

E. Mounting of Central Electrode.

The center wire electrode of the counter is held at the interior end by a small ball of soft solder, which has been formed in a glass bulb formed at the end of a closed capillary tube. This arrangement not only holds the wire but forms a guard ring for the wire preventing warping of the electric field in the avalanche region at the end of the sensitive region, and providing a sudden discontinuity in the sensitive region of the counter. The glass rod is painted with a metal coating to provide this guard shield. The other end of the wire is led through a Stupakoff seal with hollow electrode, which also provides a guard ring. The amphenol connector is provided to screw directly onto the male connector of the preamplifier.

F. Filling-gas.

Almost any type of gas may be used in proportional counters. For best results it is best to avoid any molecules of gas which have a high probability of capturing electrons and forming negative ions. Such gases are oxygen and water vapor. Therefore out-gassing of the counter by prolonged exposure to a vacuum and by heat is desirable. The gases used should be able to stop energetic charged particles at the pressures contemplated, and for the purpose the heavier noble gases are quite appropriate. A mixture of Argon (99.6% pure) with carbon-dioxide, in proportion of 90-10 was considered suitable for use throughout. This particular mixture is favorably reported (24)

to provide high electron drift velocities and to provide less dependence of multiplication on voltage.

III. Basic Calculations Applicable to Apparatus.

A. Stopping Power.

The incident protons from the Van de Graaff generator pass through the thin nickel window, and in the scattering process pass through a certain amount of the target material and possibly through any backing plate the target material may require. The alpha particle to be detected must pass through a portion of the target, the amount depending on the location of the emitting nucleus in the foil. It therefore becomes necessary in order to obtain quantitative results to know the stopping power, or energy loss, to be expected in these media for the two types of particles.

The theory of stopping power has been developed by Bohr, Bloch, Bethe, and others. (3), (5), (6), (7) The theoretical formulae derived give results which are in excellent agreement with experiment for the case of high energy, positively charged particles passing through matter of low atomic number. For media of higher atomic number the formulae require some rather complex corrections, the details of which have not been completely worked out. For incident particles of low energy, which may have fluctuations in the charge because of capture and loss of electrons, the theoretical results are quite invalid and only experiment can give satisfactory answers.

Fortunately Bethe (3) has drawn up curves of stopping power of certain substances for protons and alpha particles based on both theory and experiment for all energy values in which we are interested.

Likewise there is available some experimental data on relative stopping power which will permit determination of stopping power of the particular elements in which we are interested by judicious interpolation and extrapolation. We will make use of this method, and check it by a few calculations involving Bethe's formula for absolute determination of stopping power.

Stopping power is defined as the reduction in particle energy per unit length of particle travel through the stopping medium. It is expressed as $-(dE/dx)$. Atomic stopping power, σ , is defined as the energy loss per unit length of path divided by the number of atoms per unit cube of matter. That is,

$$\sigma = \frac{1}{N}(dE/dx) \quad .$$

Figure 3 gives Bethe's curves for atomic stopping power for protons and alpha particles of energies in the range of interest to us, passing through air. (Figure 31, Bethe and Livingston, 1937).

Relative atomic stopping power may be found by use of a theoretical formula obtained from the stopping power formula (see below), and given as:

$$s = \frac{Z \ln (2mv^2/I)}{Z_a \ln (2mv^2/I_a)} \quad .$$

Z = effective atomic number of medium.
Z_a = effective atomic number of air
m = mass of electron
v = velocity of particle.
I = average ionization potential of medium.
I_a = average ionization potential of air.

There are also available good experimental data in moderate energy

ranges. Figure 4 shows the curves plotted from experimental data. A linear plot is given by Siri for protons. (Figure 17, Siri, 1949). However, the plot made herein is on a semi-logarithmic basis to straighten out the curves a little at low energies and permit better extrapolation in that direction. In making this extrapolation for very low energies, we make the curves tend toward a value of unity at zero energy. The reason for this is apparent. Bethe and others have noted that electron excitation by a passing charged particle is very improbable if $\frac{1}{2}mv^2$ is small compared to the ionization potential of the electron concerned. Thus as particle energy decreases it is less able to excite inner electrons of the stopping medium, such effect appearing sooner for media of higher atomic number as compared to lower. In comparing the stopping power of two media, the above effect tends to equalize the number of effective electrons per atom of the substances compared. At very low energies wherein the particle has lost its charge, or part of its charge, a theoretical analysis of the relative atomic stopping power is difficult to make, but experimental data using light elements has indicated that the trend continues toward a value of unity. (Figure 37, Reference 3)

For any medium then, of given atomic number, one may interpolate in Figure 4 for the value of s, and determine stopping power by computing:

$$(dE/dx)_{medium} = \frac{s \cdot N_{medium}}{N_{air}} \cdot (dE/dx)_{air}$$

Values of N are tabulated in Table I, appended; and stopping power of

nickel and argon (diluted 10% with CO_2) for alpha particles and protons are computed and tabulated in Table II.

For a theoretical check on the above results, Bethe's formula (3), which is perhaps the most widely accepted, will be used. The basic formula (non-relativistic) is:

$$-(dE/dx) = \frac{4\pi e^4 z^2 N}{mv^2} \cdot B \quad \text{, where}$$

$B = Z \ln (2mv^2/I)$
B = stopping number
z = charge number of particle
Z = atomic number of medium
e = electronic charge

Other terms have been previously defined.

The values of I have been determined experimentally by Mano and are recorded in Table I. (19) A theoretical approach by Bloch and an emperical analysis of Wilson show that I can be given as 11.5 Z, in good agreement with experiment except for high values of Z. (5), (27)

As previously noted, this formula is valid only for particles of high velocity. For low energy particles no valid theoretical formula has yet been obtained. For moderate energies the formula may be modified to give correct results. This modification is to take account of the reduced contribution of inner electrons of the medium in slowing down the particle when the latter's velocity is such as to make $\frac{1}{2}mv^2$ equal or less than the ionization potential of these electrons.

There are two possible ways of doing this. One method, evolved in some detail by Bethe, requires analytical determination of the reduced contributions of the electrons in the K and higher shells. (3),(24)

This method is quite complex. An alternate method of using the original formula, with Z and I used as parameters so as to make theory agree with experiment, is sufficiently accurate for our purposes. (11), (3)

Table III gives the tabulated computations of this check on the results for nickel. The results of the calculations shown in Tables II and III are seen to agree well except for low energies where the theoretical approach is not as accurate.

The data from Table II is used to obtain the energy loss of alpha particles and protons passing through the .05 mil nickel foil which is used as a window for the protons and also as a possible target for the reaction. In computing the curves for alpha particles of low energy it may be noted that the thickness of the foil is large compared to the range of the particles; and therefore it is more accurate to divide the foil into ten sheets of .005 mil thickness, and use a step-by-step procedure for computing energy changes of the particle passing through successive sheets. The results of the computations are shown in Table IV; and the energy loss curves are graphed in Figure 4.

It is also necessary to compute the energy loss of the protons as they pass through the 1.75 cm of filling gas between the window and target. Table II gives the data for a centimeter of gas at atmospheric pressure. For the given distance and any other pressure, the loss equals

$$(\text{Energy loss/cm/atmosphere})\cdot(1.75)\cdot(\text{Press. in atmospheres}).$$

The results of this computation for various pressures are given in Table V.

In all cases of slowing or stopping of charged particles in passage through matter the answers provided for range or stopping power at best represent only an average, since the stopping process is statistical in nature. It is therefore of value, in the cases we are interested in, to obtain the standard deviation from the mean energy losses hitherto computed.

The status of the straggling theory is even less well-defined than the theory of stopping power. Again the theory is best for high speed particles passing through light media. The cases of interest to us - fairly slow particles through somewhat heavy media - have not received good theoretical foundations. Bohr (7) gives a formula which he states is not very accurate for heavier atoms, but which can at least give the correct order of magnitude of the straggling. The standard deviation from the mean of energy loss of a charged particle through matter is given by the following formula (rearranged according to Marsden and Venkateswarlu (20)):

$$\Omega^2 = \frac{4\pi z^2 \; e^4}{M} \cdot \frac{Z_o t}{A}$$, where

Ω = standard deviation in energy loss (ergs)
M = weight of particle (g.)
t = thickness of stopping medium (g/cm^2)
A = atomic weight of stopping medium
Z_o = atomic number of stopping medium

To find the straggling of the protons in passing through the window foil we note that 0.05 mil of nickel is equivalent to 1.13 mg/cm^2. Then by substitution of standard data in the formula we see that:

$$\begin{aligned} \Omega^2 &= 2.16 \times 10^{-16} \ \text{ergs}^2 . \\ &= 0.84 \times 10^{-4} \ \text{Mev}^2 . \\ \Omega &= 0.0092 \ \text{Mev.} \end{aligned}$$

As this result cannot be considered very accurate, we can conclude only that the straggling deviation is on the order of 0.01 Mev for the protons through the nickel foil.

For alpha particles through the foil, we may note that both numerator and denominator are multiplied by a factor of four; and again we find that straggling deviation is on the order of 0.01 Mev.

For protons passing through the filling gas, we note that 1 centimeter of the gas at atmospheric pressure is equivalent to about 1.8×10^{-3} g/cm^2. For 1.75 centimeters of the gas at various pressures we therefore find that the thickness in g/cm^2 equals

$$3.15 \times 10^{-3} \times p \text{ (atmospheres).}$$

Substitution in the above formula will give Ω^2_{gas}; and the total deviation for window foil and gas equals $\sqrt{\Omega^2_{gas} + \Omega^2_{foil}}$. Both Ω_{gas} and Ω_{total} are calculated and listed in Table VI. It will be noted that in all cases of interest herein, the total standard deviation for protons is still on the order of 0.01 Mev.

B. Ranges.

In theory, ranges of charged particles can be computed by integra-

tion of the stopping power formula (or tabulated data).

$$R = \int_0^{E_0} \frac{dE}{-(dE/dx)} .$$

Any inaccuracies in the stopping power formula or data will give corresponding errors in the range computations. The statistical deviations in stopping power will also provide straggling in range. For particles of moderate initial energies there are experimental data which may be used to check the theoretical computations. Range curves have been computed (3),(24) for various materials based on both theoretical and experimental considerations, which we may use (at least in part) for determination of the ranges of particles in the filling gas at various pressures.

Table VII gives the data on which our curves are based. It may be noted that the gas considered is pure argon, as the presence of 10% of CO_2 is not considered to have an effect comparable to the uncertainty in the correctness of the basic data. For comparison of the ranges of protons and alpha particles we make use of the formula (4),(3):

$$R_p = 1.0072\, R_\alpha - 0.20 \quad (\text{cm}) ,$$

where the protons and alpha particles compared have the same velocity.

In comparing data for ranges in argon and air, we determine the relative ranges in the two gases, and note how the ratio seems to approach a value close to unity for the higher range of energy in which we are interested.

The range curves are plotted in Figures 5 and 6.

C. Specific Ionization.

In the selection of values of the experimental variables (such as gas pressure) one of the factors to be known is the specific ionization of each of the particles passing through the sensitive volume of the counter. Precise data is not needed, and therefore it is not considered necessary to present the Bragg curves of ion-pairs per centimeter throughout the length of path. Suffice it to say that for moderate and high energies the alpha particle has a specific ionization between 20,000 and 30,000 ion-pairs per centimeter in air at atmospheric pressure; and as energy is lost this figure increases until at about 0.4 centimeters before the end of the path the specific ionization is between 60,000 and 70,000. For protons the specific ionization is about 1/4 that of the alpha particle at higher energies, and about 1/3 at the point of maximum ionization. (14), (25)

The above data may be applied roughly to the filling gas used. The mean ionization energy of argon is about 22% less than that of air (23), which fact would indicate an increased numer of total ions produced for particles of the same energy. However, the longer range of particles in argon tends to keep specific ionization roughly the same as in air.

D. Heating Effects.

Almost all of the energy lost in the stopping or slowing of particles (at energies of interest here) appears in the form of heat. The materi-

al which finally stops the particle beams is of sufficient mass to carry off this heat without undue trouble. However, the foils constituting the proton window and possibly the target are quite thin; and it is desirable to calculate the heating effects appearing here. As the foils are similar in both places a calculation for the window will do for both.

Consider the window as a thin disc of diameter 0.5 cm., thickness 0.000127 cm., with its circumferential boundary attached to an infinite and perfect absorber of heat which remains at room temperature. For computational purposes assume that protons of 1 Mev energy pass through, in amount represented by 1 microampere of current. At this energy the foil should absorb about 14.5% of the beam energy, or 0.145 watts. The heat flow equation without sources is (26):

$$\frac{\partial u}{\partial t} = \frac{k}{c\rho} \nabla^2 u \quad . \qquad (1)$$

The heat flow equation with source is:

$$\frac{\partial u}{\partial t} = \frac{k}{c\rho} \nabla^2 u + \frac{f(x,y,z,t)}{\rho c} \quad . \qquad (2)$$

k = conductivity (cal/cm-sec-degree)
c = specific heat (cal/gm-degree)
ρ = density (gm/cm^3)
u = temperature (degree)
f = strength of source (cal/cm^3-sec)

Case I. Assume that heat from proton energy loss is applied uniformly to foil.

The steady-state solution is what we are interested in; therefore we take $(\partial u/\partial t) = 0$. We then get

$$\nabla^2 u + K = 0 \quad , \text{ where } K = f/k \quad . \qquad (3)$$

For the symmetrical condition here, we can take u as a function of r only. Then

$$(1/r)\cdot(du/dr) + (d^2u/dr^2) + K = 0 \quad . \qquad (4)$$

If we let $p = (du/dr)$, the equation is easily solvable since it can be made into an exact integral, to give:

$$pr + \tfrac{1}{2}Kr^2 = C_1 \quad . \qquad (5)$$

For a boundary condition we can use the fact that $p = 0$ when $r = 0$. This gives us that C_1 is zero, so that

$$r\,(p + \tfrac{1}{2}Kr) = 0 \quad . \qquad (6)$$

We may cancel out r, and replace p by du/dr, giving an easily solvable equation as follows:

$$u = C_2 - \tfrac{1}{4}Kr^2 \quad . \qquad (7)$$

Another boundary condition is that $u = T$ when $r = R$, where T is room temperature, and R is radius of the foil.

This gives

$$C_2 = T + \tfrac{1}{4}KR^2 \quad . \qquad (8)$$

Then

$$u = T + \tfrac{1}{4}K\,(R^2 - r^2) \quad . \qquad (9)$$

We know that u_{max} occurs where $r = 0$, therefore

$$u_{max} = T + \tfrac{1}{4}(fR^2/k) \quad . \qquad (10)$$

If W = total energy absorbed per second by the foil,

$$f = W/\pi R^2 t \quad , \text{ and} \qquad (11)$$

$$u_{max} = T + (W/4\pi kt) \quad .$$

For nickel, $k \doteq 30$ Btu/hr-ft-degreeF $= .519$ watts/cm-degreeC

We may use watts instead of cal/sec, since this unit cancels out, when we use W in watts.

Substituting given data, then, we find that

$$u_{max} = 25^{\circ}C + 175^{\circ}C = 200^{\circ}C \quad . \tag{12}$$

Note that this is independent of R.

Case II. Assume that the heat from the proton energy loss is applied to a spot in the center of the foil, 1/64" in diameter.

The foil may be divided into two regions:

In region ①, $0 \leq r \leq a$;

In region ② $a \leq r \leq R$; where in our problem

a is 1/128" and R is 0.1 .

In region ① the equation with source applies and we may start from equation (7):

$$u_1 = C_2 - \tfrac{1}{4}Kr^2 \quad . \tag{13}$$

In region ② no source is present and we start from equation (5) with K equal to zero:

$$p_2 r = C_1 \quad . \tag{14}$$

Replacing p_2 by du_2/dr and solving we obtain:

$$u_2 = C_1 \ln C_3 r \quad . \tag{15}$$

We have the following boundary condition:

$$\begin{aligned} \text{When } r &= R, & u_2 &= T \; ; \\ r &= a, & u_1 &= u_2 \; ; \\ r &= a, & du_1/dr &= du_2/dr \quad . \end{aligned}$$

If we substitute these conditions in equations (13) and (15), we obtain three equations which can be solved simultaneously to find the

three constants of integration. This gives:

$$C_1 = -\tfrac{1}{2}Ka^2 \quad . \tag{16}$$

$$C_3 = \frac{1}{R} \cdot e^{-(2T/Ka^2)} \quad . \tag{17}$$

$$C_2 = \tfrac{1}{4}Ka^2 + T - \tfrac{1}{2}Ka^2 \ \ln (a/R) \ . \tag{18}$$

Substituting for C_2 in equation (13), we obtain:

$$u_1 = \tfrac{1}{4}K(a^2 - r^2) + T - \tfrac{1}{2}Ka^2 \ \ln \ (a/R) \ . \tag{19}$$

As before, u_{max} occurs when $r = 0$.

$$u_{max} = T + \tfrac{1}{4}Ka^2 \ (1 + \tfrac{1}{2} \ \ln \frac{R}{a}) \ ; \tag{20}$$

$$= T + \frac{P\ (1 + \frac{1}{2} \ln (R/a))}{4\pi\ kt} \quad . \tag{21}$$

Substituting numerical values in this equation, we obtain:

$$u_{max} = 25^\circ C + 400^\circ C = 425^\circ C \tag{22}$$

The actual condition expected to be encountered is somewhere between the cases I and II, which may be considered extremes. Case II is probably closer to actual conditions. We can see that the temperature rise is appreciable but not yet close to the melting point of the nickel (1452° C).

E. Proton Scattering.

Since discrimination against scattered protons is one of the most important functions of the apparatus herein devised, it is necessary to get a quantitative picture of proton flux which can be expected to pass through the counter under usual operating conditions. The scatterer is the nickel target foil, and the geometry is narrowed by the fact that a scattered proton must go through the .056" ~~1/16"~~ hole in the reaction

chamber in order to get into the counter proper.

As a representative case it will be assumed that 1 microampere of protons hits the target foil and is scattered at a laboratory angle of 150°, and with an energy of 1 Mev.

In the center-of-mass system, the scattering angle may be given by the following formula, derivable from simple classical considerations:

$$\theta = \Theta + \arcsin\left[\frac{M_p}{M_{Ni}} \sin \Theta\right]$$

$$= 150^\circ \; 29.3'$$

Similarly, in the center-of-mass system, one finds that the energy of the incident proton:

$$E = E_o\left[\frac{M_{Ni}}{M_{Ni} + M_p}\right]$$

$$= 0.983 \text{ Mev.}$$

The velocity of the proton at this energy is 1.37×10^9 cm/sec. The reduced mass equals:

$$M = \left[\frac{M_p\,M_{Ni}}{M_p + M_{Ni}}\right]$$

$$= 1.645 \times 10^{-24} \text{ grams.}$$

Rutherford's scattering formula is as follows:

$$n(\theta)\cdot d\Omega = n_o N t \left(\frac{e^2 z Z}{2 M v^2}\right)^2 \cdot \operatorname{cosec}^4 (\theta/2)\cdot d\Omega \quad .$$

The number of incident particles per second, n_o, is the number of

electronic charges to give one microcoulomb. This number is 6.24×10^{12}.

Substitution of above data and known physical constants into the formula, we get for Rutherford scattering of the protons by the nickel foil:

$$n(\theta) = 9.14 \times 10^7 \text{ per steradian per second.}$$

The solid angle presented equals:

$$\delta\Omega = \frac{\text{Area of hole}}{(\text{Dist. from target to hole})^2}$$

$$= 1/2580$$

Therefore the number of protons passing into the counter proper

$$= 9.14 \times 10^7 / 2580 = \overset{35,400}{\cancel{40,800}} \text{ per second.}$$

In scattering cases, one must at times expect deviations from Rutherford's formula. Such are not always easy to predict; but in this case we feel some confidence in the above results because the energy of the incident proton is much less than the expected height of the potential barrier. Use may also be made of the theoretical criteria developed by Bohr (7). To do this two parameters must be computed:

$$\varkappa = \frac{4\pi Z e^2}{hv} = 8.9$$

$$\zeta = \frac{2 Z^{4/3} e^4 m_e}{v^2 \hbar^2 M} = .0024$$

When $\varkappa$ is greater than 1, and ζ is less than 1, it means that the "collision diameter" is smaller than the electronic radius, but larger than the deBroglie wave-length of the proton. Under these circumstances Bohr declares that classical considerations are valid

almost all scattering angles.

IV. Possible Uses and Techniques with Apparatus.

One of the great advantages to this apparatus is its flexibility. It is easily assembled and disassembled, which will permit replacement of a portion by a modified piece if desired. Furthermore, it is capable of giving rough quantitative data for almost every aspect of a proton-alpha reaction - cross-section, energy of reaction, range of scattered protons and emitted alpha particles. It is also suited to being put onto a coincidence circuit which will enable coincidences between alpha particles and possible gamma rays to be detected. And finally, the apparatus may be useful for other experiments besides the one for which it is originally intended.

A. Techniques to Aid Discrimination.

As can be seen from preceding sections, the main difficulty to be overcome is the discrimination of alpha particles against the protons. Since we can expect several thousand protons per second through the solid angle subtended by the entrance port, this is quite a problem. As we have seen, 1 microampere of proton current will give 35,000 protons per second through the sensitive volume. Such a flux would probably saturate the counter and prevent counting altogether of alpha particles, or at least seriously vary the multiplication factor of the proportional counter. Since it takes about 100 microseconds to sweep away the positive ions from the Townsend avalanche (24), it would be more desirable to keep the proton flux down to a figure of, say, 4000 per second. This would require a proton beam incident on

II. [illegible]

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As may be seen from preceding sections, the main difficulty is in [illegible] in the [illegible] of [illegible] [illegible] [illegible] [illegible]. [illegible] 35,000 [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] of the [illegible] [illegible]. [illegible]. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

the target foil of 0.1 microamperes. It is desirable, however, to check the operation of the instrument with a known proton-alpha reacting element, using various proton beam strengths to determine just how high one can go without seriously hampering alpha counting.

A lower proton flux also aids in lowering the statistical probability of random superposition of two or more proton pulses which may be confused with an alpha pulse. If we assume for the sake of discussion that pulses pyramid if they occur within 1 microsecond of one another, the probability of the occurrence in one second of the pyramiding of n pulses (where the average counting rate is N per second) is approximately:

$$\left(\frac{N}{10^6}\right)^{n-1} .$$

To get an idea of the order of magnitude in our case, assume that N is 4000. Then we could expect that a double proton pulse has a probability of 1/250 of occurring in 1 second; a triple pulse has only 1 chance in 62500; and higher orders are negligible. To pick a worse case, suppose that N is 10,000 and that pulse time is to be 5 microseconds. Then our probability becomes $(1/20)^{n-1}$. Thus double pulses can be expected once every 20 seconds on the average; triple pulses once every 400 seconds; and quadruple pulses once every 8000 seconds. This factor is thus seen not to be serious if precautions are taken; but it still must be accounted for when analysis is made of results.

The main precaution to be taken is to see that the apparatus is

used in such a way as to minimize the effect of pyramiding. The use of low proton fluxes and short resolving time has been mentioned. This cannot always be accomplished as more paramount considerations may apply. Another way to help the situation is to regulate the pressure of the counter gas so that a maximum ratio of alpha ionization to proton ionization is obtained. If the scattered protons have a longer range than the expected alpha particles, it would be well to make the pressure of the gas rather low permitting the most energetic alpha particles to traverse most of the sensitive volume while the protons pass beyond and expend most of their energy in the counter walls. On the other hand, for proton ranges shorter than the alpha particle ranges, it is quite simple to increase the pressure to stop the protons just before reaching the sensitive volume while letting alpha particles into the zone. By this means one should usually be able to prevent any appreciable chance of counting pyramided proton pulses as an alpha pulse.

It is desirable, if difficulties with discrimination are not expected, to make the pressure such as to stop the alpha particles just short of the end of the sensitive volume. This gives the maximum pulse size, permits detection of the greatest number of different alpha energies, and minimizes the effect of straggling.

After selection of the gas pressure, the voltage must be chosen for the central electrode from curves of multiplication versus voltage for the specific pressure selected. This multiplication factor should be on the order of several hundred. Too high an amplification puts one

in the limited proportionality region, making discrimination more difficult. On the other hand if we use a short resolving time for which the instrument is designed, we get a smaller pulse height; and the multiplication factor must be kept fairly large to overcome this effect. The multiplication factor should not be placed below 100 unless unavoidable.

B. Reaction Cross-section.

The reaction cross-section is easily computed, in theory at least. The number of protons per second is easily determined by accumulating their charge in the reactor section and measuring it in the current integrator attached electrically thereto. In practice this is subject to certain errors which are not easily determinable, but can be minimized. Protons which hit the side of the Faraday cage are measured even though they do not hit the target. Also protons may cause secondary emission of electrons as they hit the sides of the apparatus. The first effect may be minimized by collimating the proton beam well before it enters the cage; the second, by placing the Faraday cage and the reaction chamber at a positive potential with respect to adjacent pieces to draw back most of the electrons ejected by proton collisions.

The number of alpha particles ejected can be determined actually only in the direction of the counting apparatus. If ejection is random in direction then the total emission is determinable from the geometry of the entering port. On the other hand, if directional effects are occasioned we can determine reaction cross-section only for the given angle of emission. To get complete reaction cross-

section, the directional effects would have to be determined. Coincidence analysis of gamma radiation may help in this regard.

C. Proton Scattering Cross-section.

It is obvious that cross-section for proton scattering can easily be determined from the proton counts in the chamber. Beam currents may be cut down to whatever intensity necessary to prevent "drowning" of the counter. The values obtained are of course applicable only to the particular angle of the apparatus.

D. Range and Energy of Alpha Particles.

The mean range of the alpha particles may be obtained roughly by use of a cathode ray oscilloscope connected to the amplification output of the amplifier-discriminator, so that the maximum pulse height may be observed. It may be noted that if the initial measurements are made with the gas pressure adjusted to stop the alpha particles within the sensitive volume, then additional runs may be made with pressures decreased in successive increments. At a certain pressure, then, the alpha particles will begin to pass beyond the sensitive volume; and a rather sudden diminishing in pulse size should be expected. (This is due to the fact that maximum ionization occurs shortly before the end of the path of the particle.) If we know the pressure at which this effect starts, then we may go the range-energy curves for the filling gas (adjusted for the ratio of gas filling pressure to atmospheric pressure) to find the energy. Conversion from laboratory to center-of-mass coordinates is accomplished

~~by the usual~~

by the usual methods; although for moderately heavy elements, the correction is probably less than the experimental error in this method.

It is possible to reverse the procedure, and increase the gas pressure until the alpha particles can no longer reach the sensitive volume; but this effect will probably not give as great accuracy as the one described above.

E. Coincidence Measurements.

The coincidence possibilities are easily understood and have been previously indicated. The output of the discriminator is a pulsation - each pulse of 10 volts in size and 1 microsecond in duration. This permits discrimination within an interval of that order. Apparatus for gamma measurement and coincidence counting are not a part of this thesis. The target is located in such a place on our apparatus as to facilitate placement of the gamma counter tube at almost all angles with respect to said target and the direction of the proton beam.

It should be noted that in making coincidence measurements one must account for the random coincidences which are possible due to two main causes: (1) a true i pulse from one counter along with a random background count on the other; (2) a chance coincidence between an alpha particle ejected from one nucleus and a gamma ray emitted from another at the same time.

F. Study of Short-lived Radioisotopes.

Since the apparatus is to be attached directly to the source of

particles and measurements can be made simultaneously with or immediately after bombardment, an excellent means is provided for study of half-lives of certain isotopes which decay so rapidly as to prevent the usual method of study by bombardment and subsequent removal to a counting apparatus. It may be possible to find an isotope of a few seconds' half-life which could be measured immediately after bombardment and which could be produced by a proton or deuteron capture. This is not the fundamental use for which the apparatus is devised; but with slight modification it may be used so.

V. Operating Characteristics and Tests.

A. Counter Amplification Characteristics.

In operation of the counter tube in the proportional region it is desirable to know the counter amplification factor, for reasons given hitherto. Korff (17) has developed a theoretical formula for this factor, which depends on the following parameters: size of the central electrode; amplification threshold voltage; operating voltage; capacity of the counter tube; number of atoms per cubic centimeter ofthe filling gas; and a facter related to ionization cross-section of the gas. This formula has several defects from a practical point of view: (a) the curve of amplification versus applied voltage may begin with a rather gentle slope, so that the threshold voltage for amplification is difficult to adjudge; (b) the capacity of the counter is not easily determined when irregularities of the tube are considered; and (c) the ionization cross-sections of only a few elemental gases are known with any precision. For our purposes the last defect is particularly important, since we are using a mixture of gases.

The amplification factor for the counter tube may however be obtained readily by experiment for any specific set-up according to a procedure outlined by Rossi and Staub (24). This technique was used by us and is outlined as follows:

A polonium source, obtained by evaporation of a radioactive solution on a tantalum disc, was inswsted in the target section. The counter was filled with the proper mixture of gases with the required pressure, and then it was put into operation.

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The output of the amplification section of the linear amplifier was connected to a cathode-ray oscilloscope, thus permitting observation of the individual pulses. For various voltages on the central electrode the variation in pulse height could be used to ascertain the tube amplification - the basic reference being the pulse height when the voltage was so low as to insure the counter operation in the ionization region (amplification in the counter being unity at this point). Actually a slight deviation from this procedure was used. The attenuation control on the linear amplifier is accurately calibrated, and the amplification of the counter tube was determined by the amount of attenuation required to keep the pulse height the same as the reference.

The procedure was carried out at various gas pressures varying in steps of 50 millimeters of mercury, from 50 mm to 250 mm. Difficulties initially were encountered in obtaining reproducible data for various calibration runs at the same pressures. It was determined that this was due to lack of care in accurate adjustment of gas percentages in the filling process, and to the leakage of some variable amounts of air. With all possible care and precautions to maintain constancy in gas quality, the results improved. A consistent set of results was finally obtained, and is plotted in Figure 7.

B. Operation of Counter with Internal Source.

In order to assure ourselves that the counter will operate successfully and to check some of the practical aspects of its operation, a discrimination curve was obtained by taking counts on the polonium

sample mentioned above. The data for this is tabulated in Table VIII; and the results are indicated in Figure 8. It is seen that a good plateau is obtained, within the limitations of statistical variations. The dropping off of the counting rate at the extremely high pulse heights is due partly to normal alpha particle straggling but more to the self-absorption of the sample film.

The strength of this source is computed as a matter of interest:

$$\text{Activity in } \mu C = \frac{(\text{counts/min.}) \times 4\pi}{60 \times \omega \times n \times 3.7 \times 10^4}, \text{ where}$$

counts/min. = 842 ± 8

ω = solid angle subtended by entrance port,

= 1/2580

n = number of alpha particles per disintegration,

= 1.

Substituting this data in the above equation we find that the activity on the date measured (14 May 1951) was 12.3 μC.

C. Test Using Protons from the Van de Graaff Generator.

Several attempts have been made to use protons from the Van de Graaff generator to induce a proton-alpha reaction in the apparatus, using fluorine (in the form of TaF_5 obtained by the reaction of hydrofluoric acid with a tantalum target disc) as the target element. These attempts have not been conclusive and the data from same is not included. The most troublesome phenomenon to interfere is the pick-up by the instrument of any near-by sparks or sudden voltage changes. Due to an inherent capacity existing between the Faraday

cage section and the central electrode all sudden voltage changes occasioned by condenser discharges in the integrator are counted as fairly heavy pulses - comparable to alpha particle pulses in size. A grounded shield between the Faraday cage and the counter section is indicated as necessary. Further improvements along these lines must be made before good quantitative data can be obtained from the instrument for that type of experiment in which the counter and the Van de Graaff generator operate simultaneously.

VI. Directions of Future Work.

Future improvements of the intrument should proceed along the following lines:

(a) All internal valves should be replaced with the bellows type needle valve which will hold a good vacuum on either side.

(b) Lucite parts should be replaced by glass wherever possible, because lucite does release slight amounts of gas, and also is not suitable for places where it must undergo a stress.

(c) The electrostatic shielding between Faraday cage and counter (mentioned above) must be provided.

(d) All flexible hosing should be specifically designed for vacuum work.

(e) Thorough tests should be carried out using known reactions until consistently successful results are obtained. These tests should be under a variety of conditions of gas pressures.

Table I.

Basic Data.

Element	Z	At. Wgt.	Av. Ioniz. Pot. (ev)	Density	No. atoms per cc at atmos. pr.
Air	7.23		81		2.69×10^{19}
A	18		195		2.69×10^{19}
Ni	28	58.7	325	8.85	$.913 \times 10^{23}$
Cu	29	63.5	320	8.96	$.85 \times 10^{23}$

Table II.

Computation of Stopping Power of Nickel and 90-10 Argon-CO$_2$ Mixture for Alpha Particles and Protons.

A. Alpha Particles.

E(Mev)	σ_{air}	s		σ(x10^{-15})		$-dE/dx$ (Mev/cm)	
	(x10^{-15})	Ni	Gas	Ni	Gas	Ni	Gas (1 atm.)
.3	37.5	1.32	1.23	49.5	46.1	4520	1.24
.4	40.8	1.37	1.28	55.9	52.2	5100	1.40
.5	43.0	1.41	1.31	60.6	56.3	5530	1.51
.6	44.7	1.46	1.34	65.2	59.9	5950	1.61
.7	45.9	1.49	1.37	68.4	62.9	6240	1.69
.8	46.6	1.51	1.40	70.4	65.2	6430	1.75
.9	47.0	1.55	1.42	72.8	66.7	6650	1.79
1.0	47.0	1.59	1.45	74.7	68.1	6820	1.83
1.2	45.5	1.64	1.50	74.6	68.3	6810	1.84
1.4	42.1	1.70	1.54	71.6	64.8	6540	1.74
1.6	39.0	1.75	1.57	68.2	61.2	6230	1.65
1.8	36.8	1.80	1.62	66.2	59.6	6050	1.60
2.0	34.5	1.85	1.67	63.8	57.6	5830	1.55
2.5	29.8	1.96	1.75	58.4	52.1	5330	1.40
3.0	26.4	2.06	1.80	54.4	47.5	4960	1.28
3.5	23.8	2.15	1.85	51.2	44.0	4670	1.18
4.0	21.8	2.23	1.89	48.6	41.2	4440	1.11
5.0	18.8	2.35	1.94	44.2	36.5	4030	.981
6.0	16.4	2.43	1.97	39.8	32.3	3630	.869
8.0	13.3	2.53	2.00	33.7	26.6	3080	.715
10.0	11.3	2.60	2.02	29.4	22.8	2690	.613

B. Protons.

.3	13.0	1.64	1.50	21.3	19.5	1950	.525
.4	10.6	1.75	1.57	18.5	16.6	1695	.447
.5	8.85	1.85	1.67	16.4	14.8	1500	.398
.7	6.90	2.02	1.78	13.9	12.3	1270	.331
1.0	5.44	2.23	1.89	12.1	10.3	1110	.277
1.4	4.30	2.40	1.96	10.3	8.43	942	.227
2.0	3.25	2.53	2.00	8.22	6.50	750	.175
5.0	1.65	2.74	2.04	4.52	3.36	412	.0905

Table III.

Theoretical calculations for stopping power of nickel for alpha particles and protons.

$$-dE/dx = \frac{4\pi e^4 z^2 N}{m v^2} B$$

$$B = Z_{eff} \ln (2mv^2/I), \text{ where } Z_{eff} = 26.4 \text{ and } I = 325.$$

Putting in constants, and changing energy units to Mev, one obtains:

$$-dE/dx = \begin{cases} 358\ B/E & \text{for alpha particles .} \\ 22.4\ B/E & \text{for protons .} \end{cases}$$

$$B = \begin{cases} 26.4 \ln (1.675\ E) & \text{for alpha particles .} \\ 26.4 \ln (6.70\ E) & \text{for protons.} \end{cases}$$

E (Mev)	B_α	B_p	$-(dE/dx)_\alpha$	$-(dE/dx)_p$
1.0	13.6	50.2	4870	1120
2.0	31.9	68.5	5710	767
5.0	56.0	92.7	4010	415
10.0	74.4	111.0	2660	249
15.0	85.0		2030	
20.0	92.6		1660	

Table IV.

Calculations for Energy Loss for Alpha Particles Through Nickel Foil of Thickness 0.00005" (= .000127 cm).

E (Mev)	-dE/dx (Mev/cm)	δE for 1/10 foil,(Mev)	ΔE for foil(Mev)
20	1660	.0211	.21
15	2030	.0253	.26
10	2680	.0340	.35
5	4030	.0512	.53
2	5830	.0740	.80
1	6820	.0866	.70
.9	6650	.0845	.66
.8	6430	.0816	.63
.7	6240	.0792	.58
.6	5950	.0755	.53
.5	5530	.0702	Almost all
.4	5100	.0647	" "
.3	4520	.0575	" "

Calculations for Energy Loss of Protons through Nickel Foil.

5.0	412	.00523	.0525
2.0	750	.00952	.096
1.4	942	.01197	.121
1.0	1110	.01410	.145
.7	1270	.01610	.175
.5	1500	.01904	.215
.4	1695	.02150	Most
.3	1950	.02475	Almost all

Table V.

Energy loss of protons passing through 1.75 cm of filling gas (90% Argon - 10% CO_2):

E(Mev)	Energy loss/cm. at 1 atm. press.	Loss for 1.75 cm.	Pressure (mmHg)	Energy Loss(Mev)
.3	.525	.918	50	.0604
			100	.1209
.5	.398	.696	50	.0458
			100	.0917
			150	.1375
.7	.331	.579	50	.0381
			100	.0762
			150	.1142
			200	.1524
			250	.1904
1.0	.277	.485	50	.0319
			100	.0638
			150	.0957
			200	.1277
			250	.1596
			300	.1914
			350	.223
1.4	.227	.397	50	.0261
			100	.0522
			150	.0784
			200	.1045
			250	.1308
			300	.1570
			350	.1830
			400	.209
			500	.261
2.0	.175	.306	50	.0201
			100	.0403
			150	.0604
			200	.0805
			250	.1008
			300	.1210
			350	.1410
			400	.1611
			500	.201

Table VI.

Calculation of standard deviations in energy losses in 1.75 cm of filling gas and in foil (.00005" nickel) plus filling gas.

$$\Omega^2 = \frac{4\pi z^2 e^4}{M} \cdot \frac{Z\rho}{A} \cdot t$$

For nickel foil $\Omega^2 \doteq .84 \times 10^{-4}\ (\text{Mev})^2$

For filling gas $\Omega^2 \doteq 2.2 \times 10^{-4} \times P_{atm}\ (\text{Mev})^2$

p (mmHg)	Ω^2_{Gas}	Ω^2_{Total}	Ω_{Gas}	Ω_{Total}
50	$.145 \times 10^{-4}$	$.99 \times 10^{-4}$	.004	.01
100	.29	1.13	.005	.011
150	.43	1.27	.0065	.011
200	.58	1.42	.0075	.012
250	.72	1.56	.0085	.0125
300	.87	1.71	.0093	.013
350	1.01	1.85	.010	.014
400	1.16	2.00	.011	.014
500	1.45	2.29	.012	.015

Note: (1) Values calculated are considered to be quite approximate.
(2) Values are theoretically independent of particle velocity.

Table VII.

Calculations of range of protons and alpha particles in argon (NTP).

A. Protons.

E (Mev)	Range(cm) *	R_{air} *	Ratio R_A/R_{air}
.5	1.0	.7	1.43
.75	1.72	1.38	1.25
1.0	2.6	2.25	1.16
1.5	4.[illegible]	4.40	1.09
2.0	7.54	7.0	1.073
2.5	(10.5)	10.25	1.03(assumed)
3.0	(13.8)	13.8	1.00 "
4.0	(23.0)	23.0	1.00 "
5.0	(34.0)	34.0	1.00 "

Range values in parentheses are derived from the ratio R_A/R_{air}.

B. Alpha particles.

Formula: $R_p + .20\ (\text{cm}) = R_\alpha$ **

E (Mev)	Range by Formula	Range by Experiment***	Range in Air**
.2			.17
.5			.30
1.0			.51
2.0	1.2		1.0
4.0	2.8		
5.3	[illegible]	4.17	3.87***
7.7		7.3	6.96***
10.0	10.7		10.55
16.0	19.5		
20.0	34.2		

References:
- * (13), (24).
- ** (3)
- *** (8)

Table VIII.

Data for Pulse Height Discrimination Curve using Polonium Source(Int.).

Discrimination Setting	Counts	Seconds	Counts/Min.	Probable Error
38			0	
36	12	60	12	3.7
34	256	48	320	11
32	512	51.5	597	16
30	1024	87.0	707	18
27.5	1024	87.9	700	18
25	1024	77.0	799	19
22.5	1024	73.1	841	19
20	1024	75.7	812	19
17.5	1024	76.5	804	19
15	1024	74.8	822	19
12.5	1024	68.5	898	20
10	1024	73.9	832	19
7.5	1024	71.1	865	20
5	1024	74.2	828	19
2.5	1024	70.1	877	20
0	1024	1.2	51200	

This data is plotted in Figure 8. Vertical bars in the figure cover the range of probable error.

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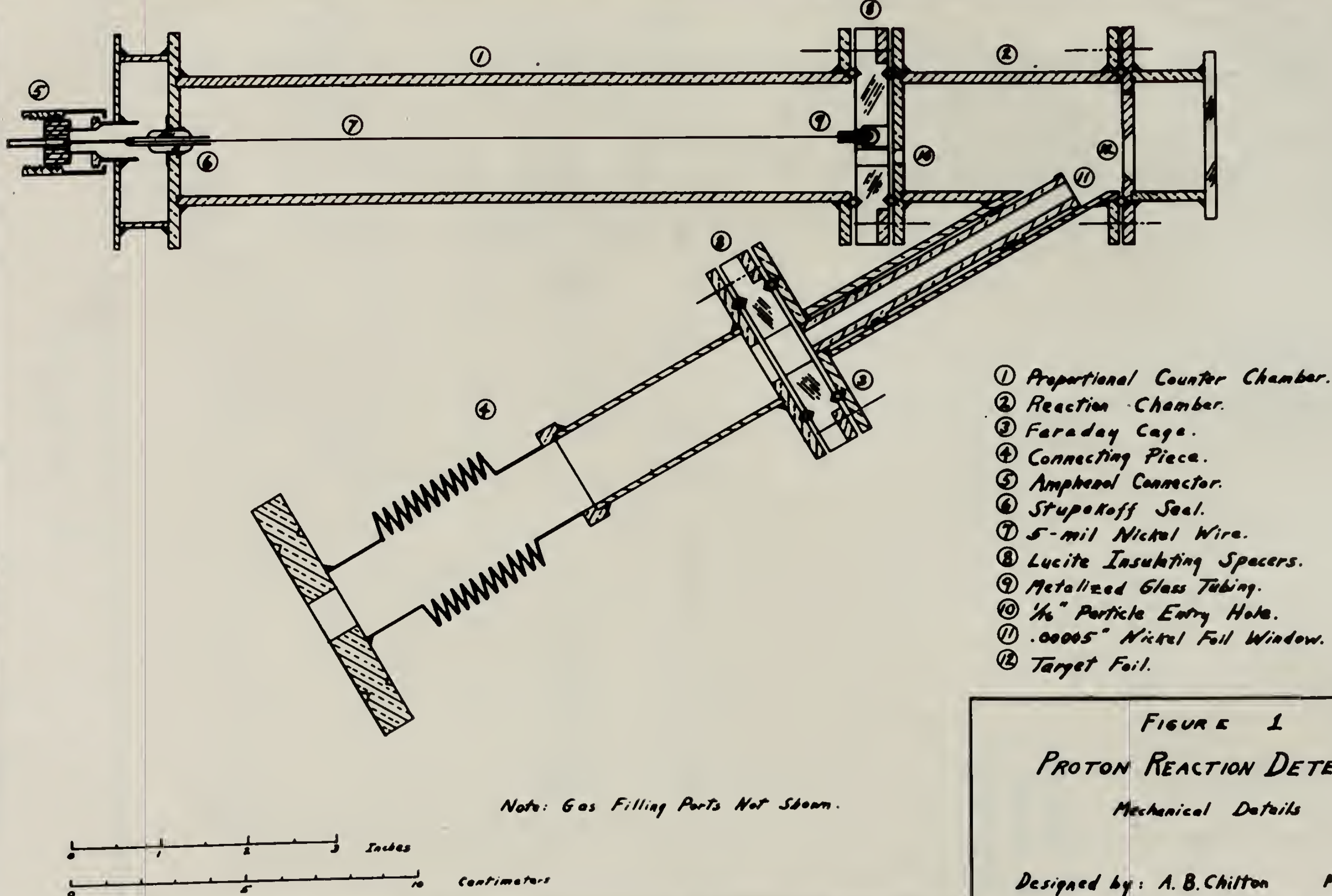
①
②
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⑧
⑨
⑩
⑪
⑫
① Proportional Counter Chamber.
② Reaction Chamber.
③ Faraday Cage.
④ Connecting Piece.
⑤ Amphenol Connector.
⑥ Stupakoff Seal.
⑦ 5-mil Nickel Wire.
⑧ Lucite Insulating Spacers.
⑨ Metallized Glass Tubing.
⑩ 1/16" Particle Entry Hole.
⑪ .00005" Nickel Foil Window.
⑫ Target Foil.
Note: Gas Filling Ports Not Shown.
0
1
2
3
Inches
0
5
10
Centimeters

FIGURE 1

PROTON REACTION DETECTOR

Mechanical Details

Designed by: A. B. Chilton May, 1951.

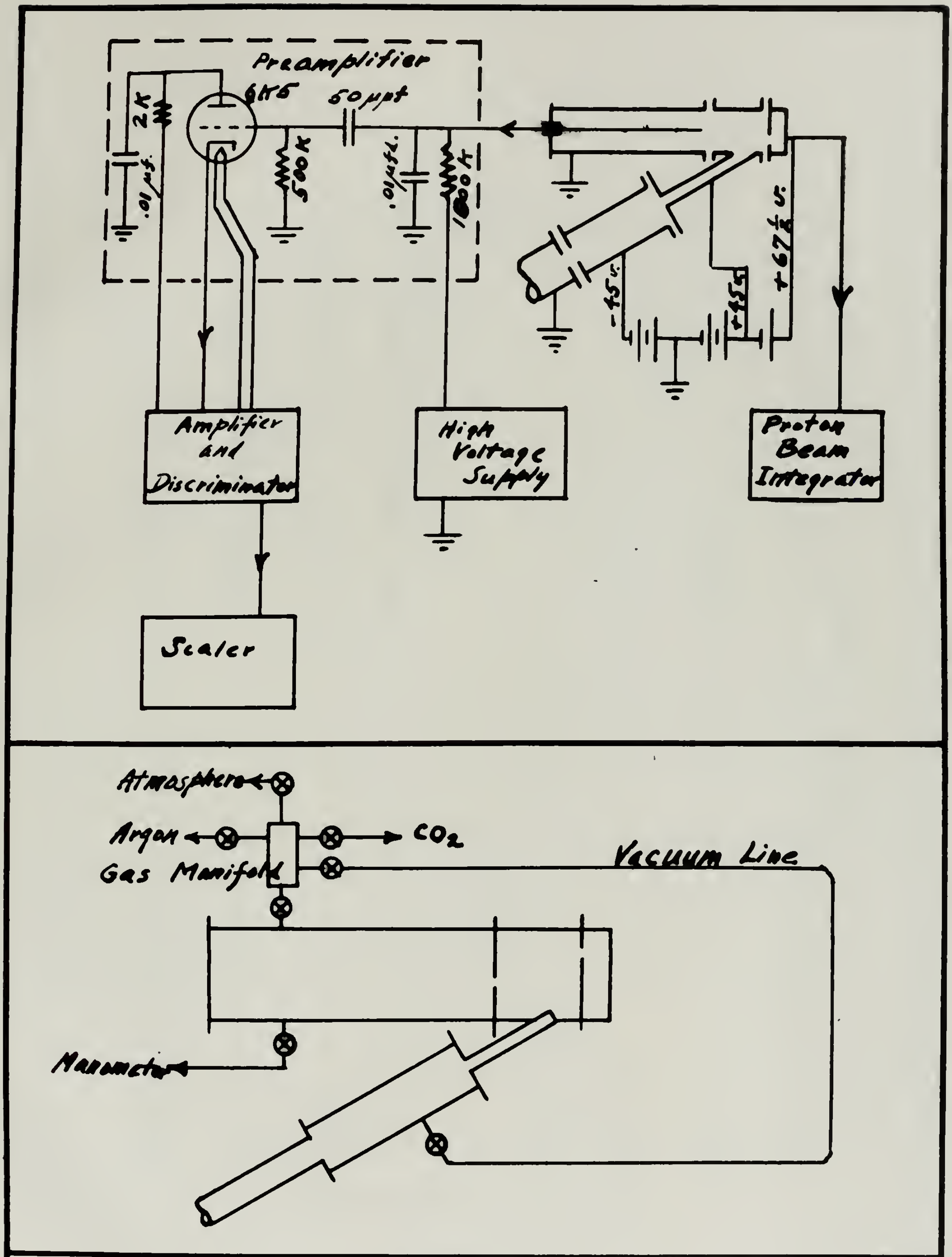


FIGURE 2.

Electronic and Gas-Filling Systems

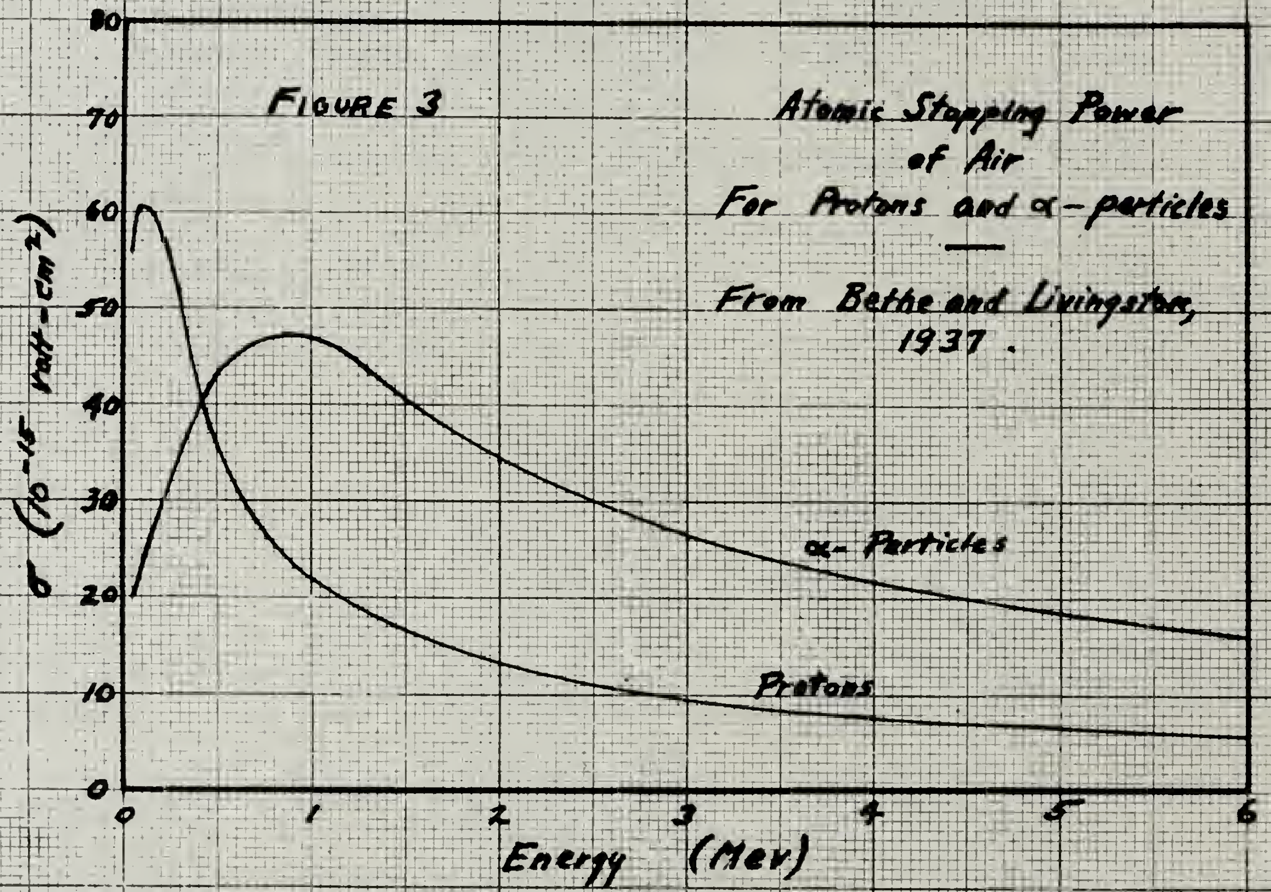
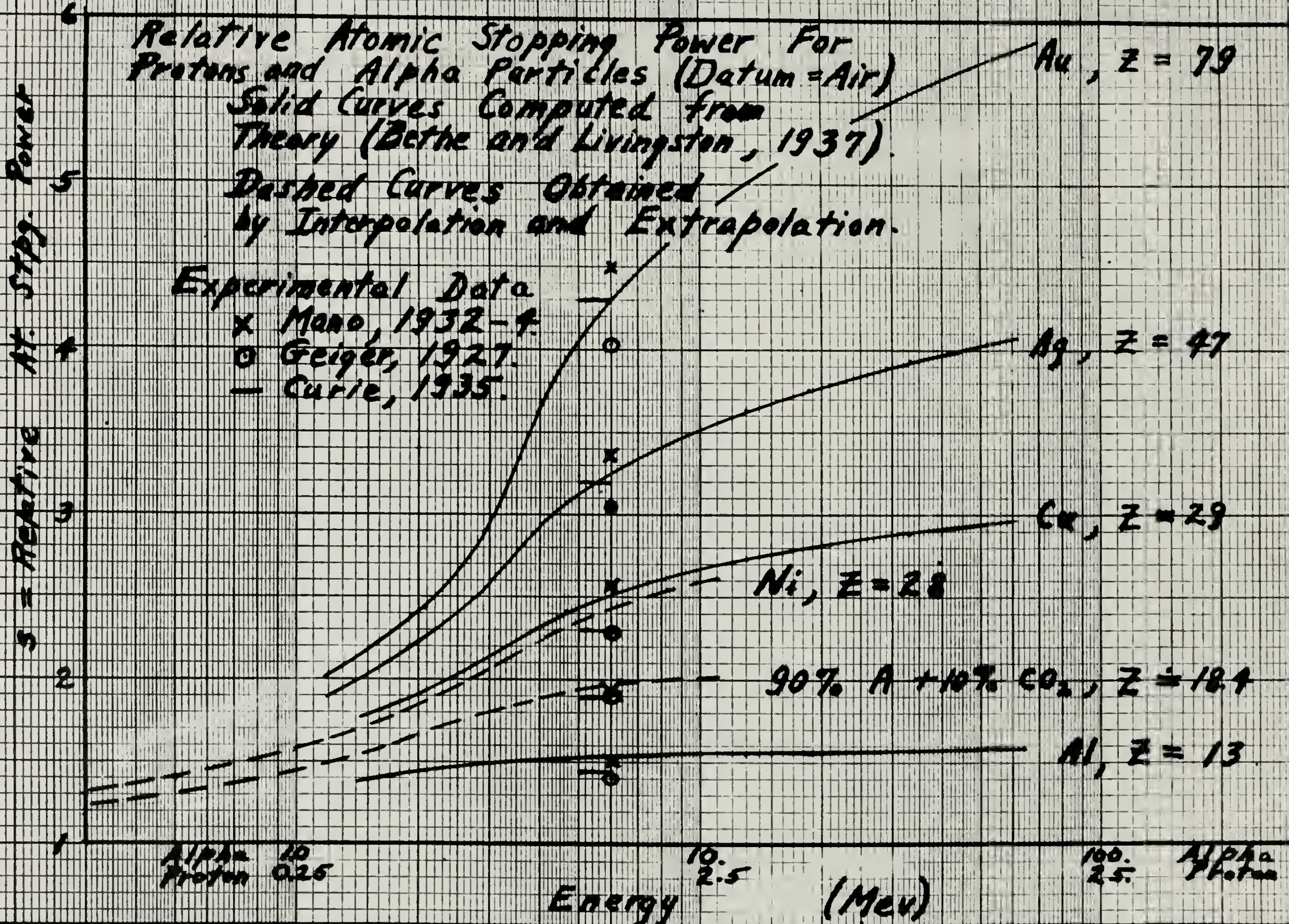


FIGURE 3

Atomic Stopping Power
of Air
For Protons and α-particles

From Bethe and Livingston,
1937.

FIGURE 4



Relative Atomic Stopping Power For Protons and Alpha Particles (Datum = Air)

Solid Curves Computed from Theory (Bethe and Livingston, 1937)

Dashed Curves Obtained by Interpolation and Extrapolation.

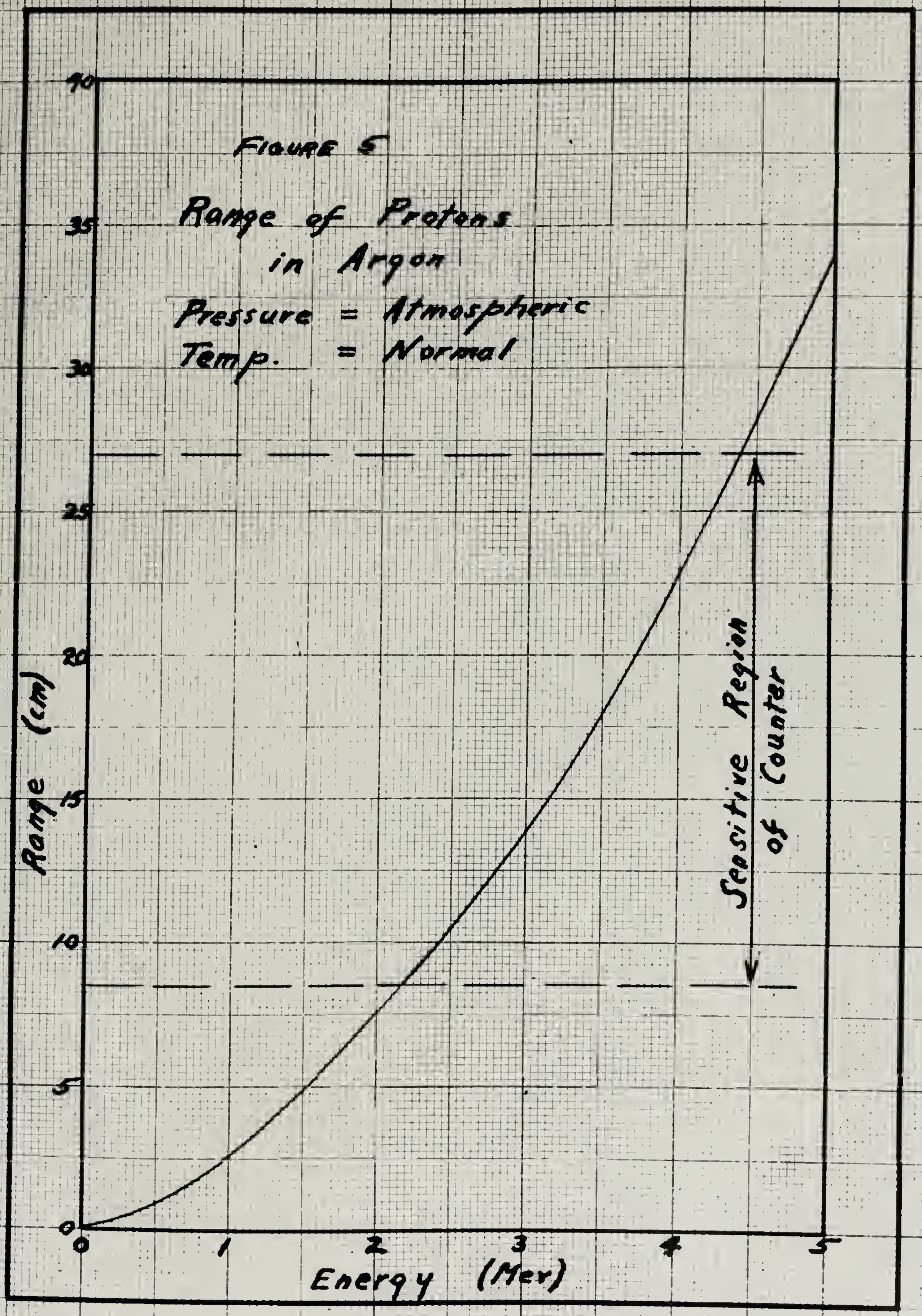


FIGURE 5

Range of Protons in Argon

Pressure = Atmospheric
Temp. = Normal

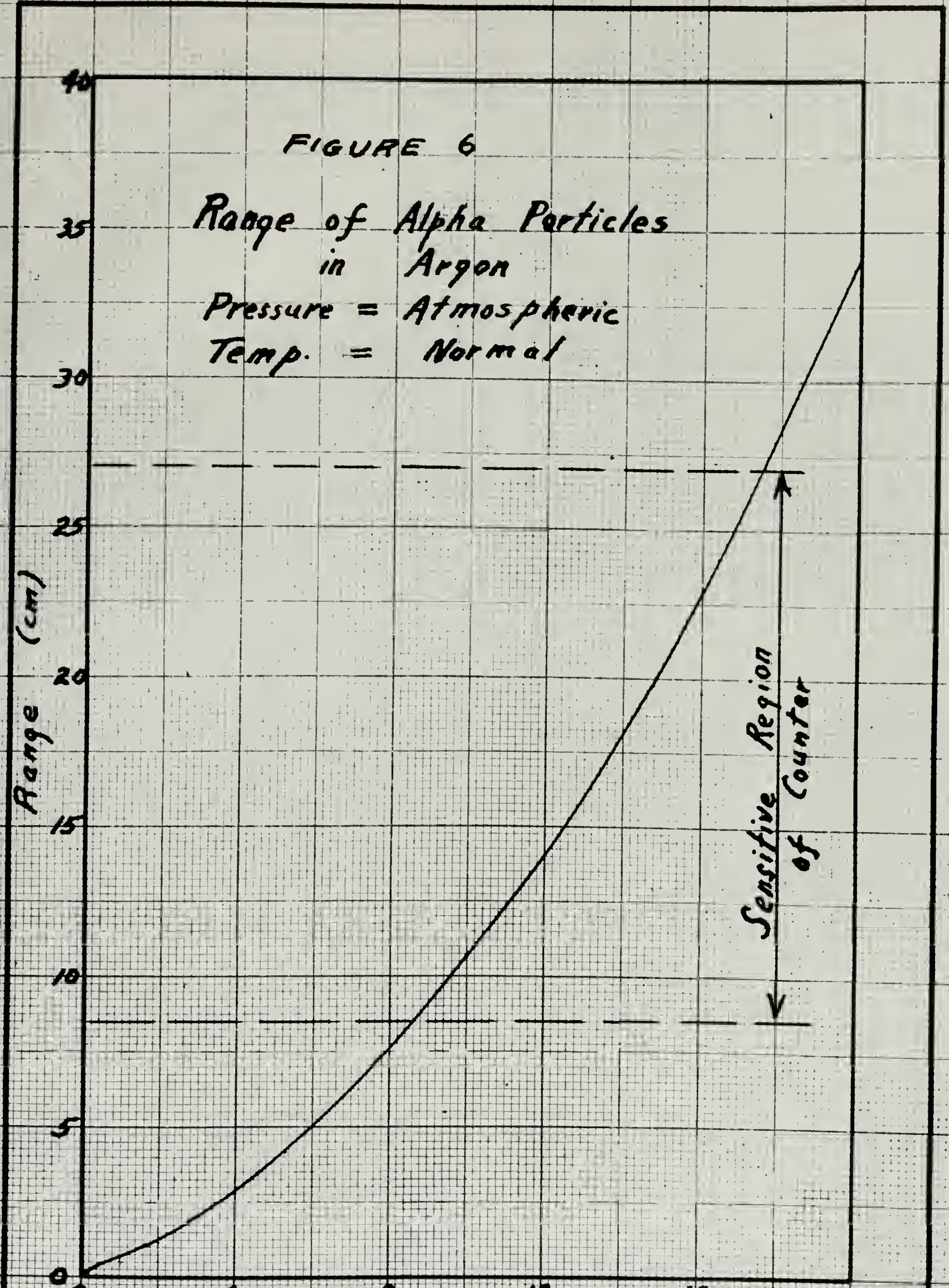


FIGURE 6

Range of Alpha Particles in Argon

Pressure = Atmospheric

Temp. = Normal

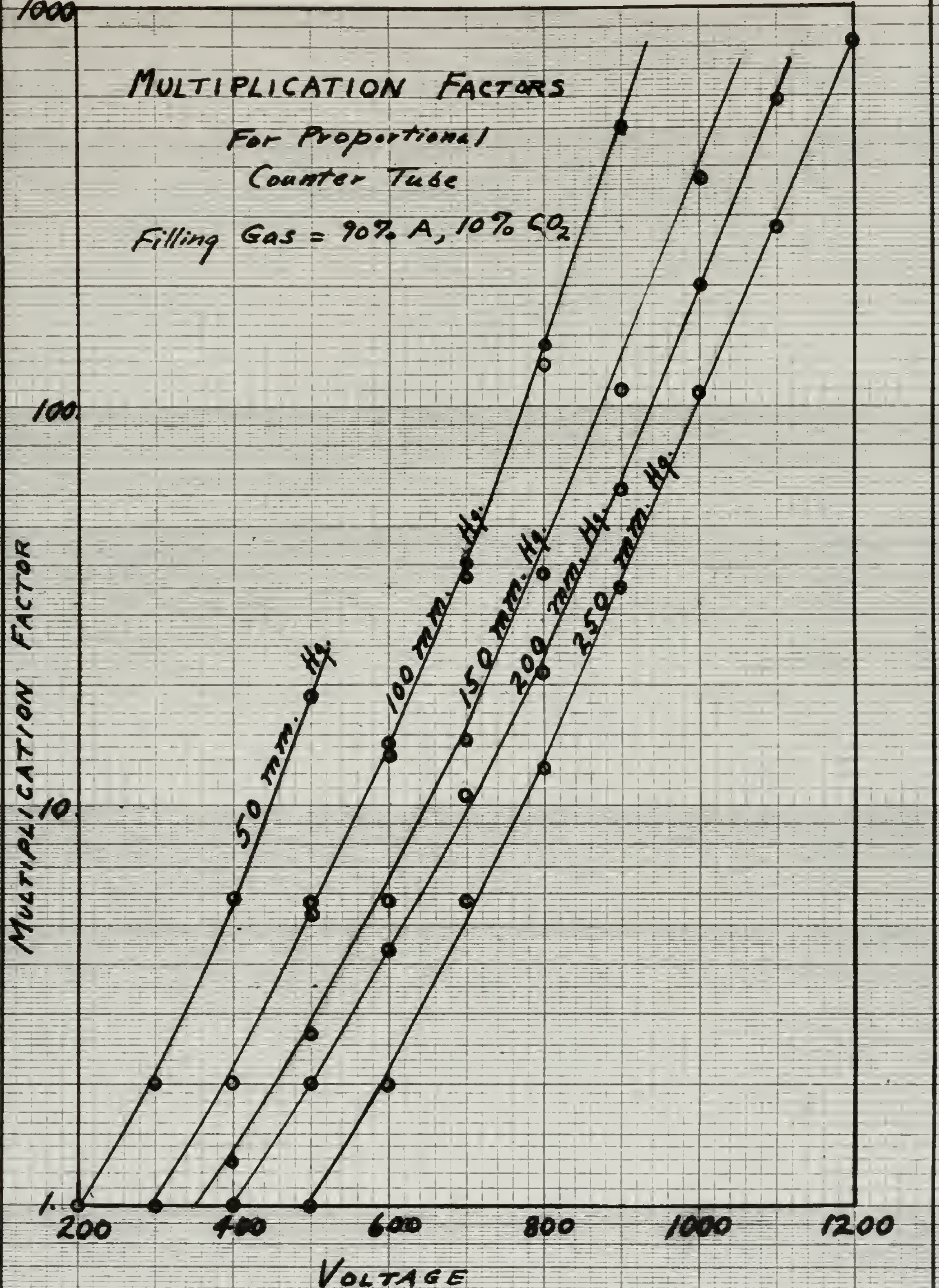

MULTIPLICATION FACTORS
For Proportional
Counter Tube
Filling Gas = 90% A, 10% CO_2
MULTIPLICATION FACTOR
1000
100
10
1.
200
400
600
800
1000
1200
VOLTAGE
50 mm. Hg.
100 mm. Hg.
150 mm. Hg.
200 mm. Hg.
250 mm. Hg.

FIGURE 7.

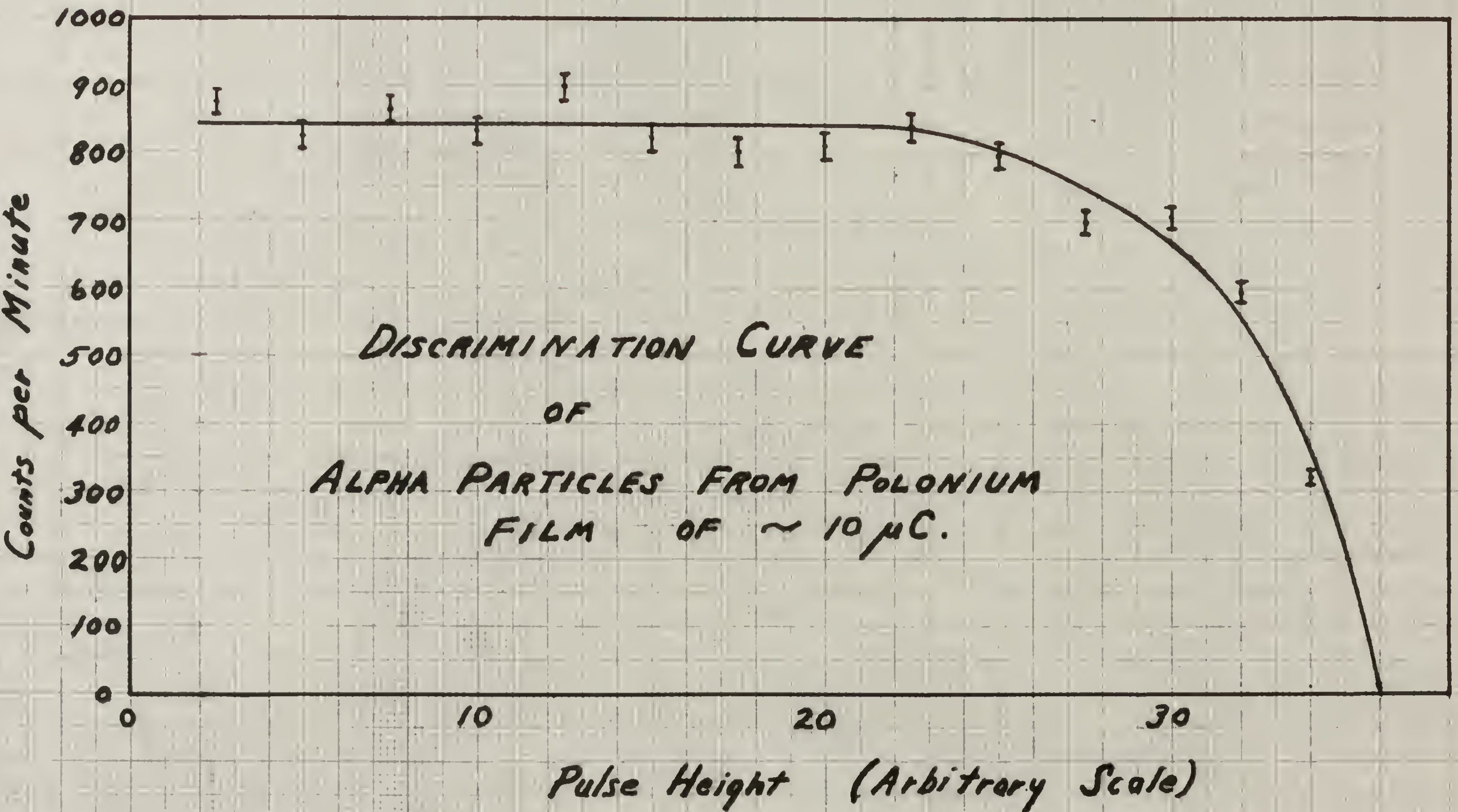

DISCRIMINATION CURVE
OF
ALPHA PARTICLES FROM POLONIUM
FILM OF ~ 10 μC.

FIGURE 8.

28809

Thesis
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